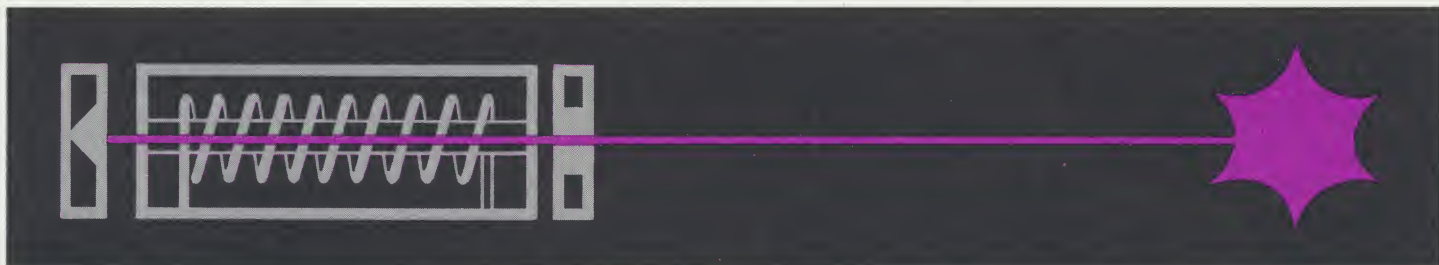# LASER-FARE

LASER SPECIFICATIONS
What Do They Really Specify?

The laser industry today, with its phenomenal expansion and its almost daily announcements of better devices demonstrating even better performance characteristics, offers a multitude of "off-the-shelf" laser systems and components that would appear to satisfy most present-day requirements. But let the buyer be aware. For his interpretation of the specifications of these devices may be of significant variance with those of the manufacturers. Indeed, this variance in interpretation exists between the manufacturers themselves.

Several factors contribute to this lack of a clear, concise understanding of laser specifications between customers and manufacturers. Laser technology requires the use of a number of relatively new parameters to characterize laser operation. This, in turn, presents problems of measurements never before encountered. Since the methods used to measure these new parameters (as well as the interpretation of such measurements) have yet to be standardized, each manufacturer has been forced to establish his own standards. Many have developed their own unique measurement apparatus. The absence of formalized laser parameters and standardized measurement techniques, combined with the fact that there are currently three different types of lasers (optically-pumped solid state, semiconductor, and gas) only adds to the confusion of this new and highly complicated field. And the importance of news and publicity releases that announce the attainment of improved laser performance becomes somewhat "grayed" if a clear definition of the parameters involved and the conditions of measurement are not provided.

Confusion is normal in the learning curve stage of any new technology. Yet many laser customers have invested heavily in determining the output parameters of the laser system required for their particular application only to be "burned" (figuratively, but expensively) by the equipment they have purchased. They ask "what can be done about it?"

This article deals with that question. For purposes of brevity, it is limited to pulsed optically-pumped solid state lasers. The discussion of particularly troublesome parameters and descriptions of measurement techniques and apparatus should provide an aid for the prospective user of this type of laser equipment.

The Most Important Parameters

The output characteristics of a pulsed optically-pumped solid state laser system can essentially be defined by the following parameters:

- **THE LASER PULSE ENERGY** — a measurement (e.g., joules) of the total energy in the laser pulse. Frequently obtained by plotting the area of the instantaneous laser output versus time.

- **THE PULSE PEAK POWER** — a measurement (e.g., watts) of the peak power attained by the laser pulse. This is the maximum point on the plot of instantaneous laser power versus time.

- **THE BEAM DIVERGENCE** — a measurement (e.g., milliradians) of the rate at which the laser radiation diverges as it radiates from the laser crystal.

- **THE SPECTRAL WIDTH** — a measurement of the spectral purity of the laser light. The output wavelength for ruby lasers is 6943 angstroms at 20°C. The expressions LINEWIDTH and FREQUENCY SPREAD refer to deviations from this center of output frequency.

- **DEGREE OF POLARIZATION** — The ratio of the difference between parallel and perpendicularly polarized light to the total light emitted.

- **JITTER** — the repeatability of the exact time of occurrence of the giant laser pulse.

- **COMPONENT LIFETIME** — In addition to the above listed parameters, estimates of the probable lifetime of the critical components that comprise a laser system should be established. These estimates should be based on data obtained while the system is operating at its specified outputs. A reasonable lifetime value will, of necessity, be dictated by the intended application. And it will vary widely, not only within the individual component. types such as flashlamps, capacitors, mirrors, crystals, Q-spoilers, etc., but also depending upon the actual experience of the laser manufacturer and his understanding of the failure phenomena.

Excellent methods of measurement exist for some of these parameters and they therefore present no problem in the communication of clear specifications between customer and manufacturer. Considerable latitude does exist, however, in the measurement and interpretation of pulse energy, peak power, beam divergence, and component lifetime specifications. The following paragraphs provide a detailed discussion of these parameters and their measurement. Several suggestions are offered for the possible standardization of specification terminology, measurement, and interpretation.

The Most Troublesome Ones

PULSE ENERGY

The giant pulse from a ruby or neodymium-glass laser represents radiation rising in a few nanoseconds to peak powers that can range from a few to several thousand megawatts. Total pulse duration ranges from only 10 to perhaps 50 nanoseconds.

How It's Measured

Numerous techniques and instruments have been used to measure pulse energy. Some of these involve the absorption radiation in a cone (Mendenhall wedge) after which the temperature rise of the cone is measured. Problems associated with this method are that all of the energy may not be absorbed in the cone or that a chemical reaction such as oxidation may take place during the process in which case the conversion of light energy to heat is not complete or reproducible.

Another technique employs what is commonly known as a "rat's nest" calorimeter. This is a maze of very fine wire in an enclosure. The laser radiation is beamed into this maze and the absorption of radiation by the fine wire causes a change in the resistance of the wire which is monitored and used as a measure of laser energy.

Other methods of measuring laser pulse energy include integrating sphere bomb calorimeters, black body absorbers, and semiconductor diode transducers.

A Standard

We have tried almost all of these here at Korad and have achieved varying degrees of success. After extensive evaluation of both the good and bad features of each device, however, we determined that a very carefully calibrated total-absorption liquid calorimeter provided the best results.

We have now developed a series of these liquid calorimeter devices to cover several of the more frenquently encountered energy ranges. They represent a reproducible device as a standard for laser energy measurements, and the calibration method can be readily traced to appropriate measurement standards.

The calorimeter cell design and consideration of the excitation relaxation mechanism of the absorbing solution have minimized errors from partial absorption of the laser's light and its degeneration into heat. The heat capacities of the calorimeter's components, the entrance window reflection, and the thermopile constants were all carefully selected and included in the calculations as a "primary" standard calorimeter was calibrated by conventional electrical heating techniques. Theoretically, these devices should have an absolute accuracy of about ±1.5%. Our standard production units are guaranteed to ±3.0% absolute accuracy. A diagram of the device is shown below.
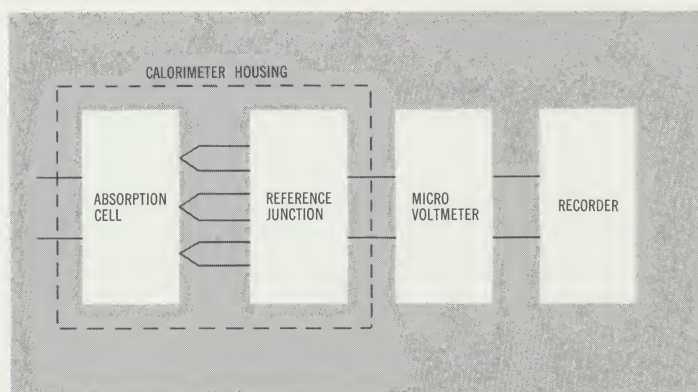
PEAK POWER

The generally accepted method of measuring laser power output involves the use of a fast-response planar diode. These diodes have a diverging lens on their front window which illuminates the entire photocathode and thus minimizes sensitivity to small variations in the direction of pointing.

Various filters are used to attenuate the laser beam and avoid saturation of the diode. The photodiode is biased through the RC network attached to the anode. In this

way, the potential of the anode is reduced proportionally to the total energy in the laser beam when a signal is received by the diode.

The photodiode is normally applied to laser power measurements by reflecting a portion of the laser beam off of a diffuse surface (such as a magnesium oxide block) into the diode, and then photographing the diode output on a fast rise oscilloscope.

Reproducible results are easy to accomplish as long as the reflecting block is fresh, the bias network utilizes precision components, and careful attention is given to the matching of the diode to the scope.

Each diode requires individual calibration using a laser calorimeter. Here again, the measurement accuracy is primarily dependent upon the accuracy of a laser energy measurement. The type of set-up used for these calibrations is shown below.
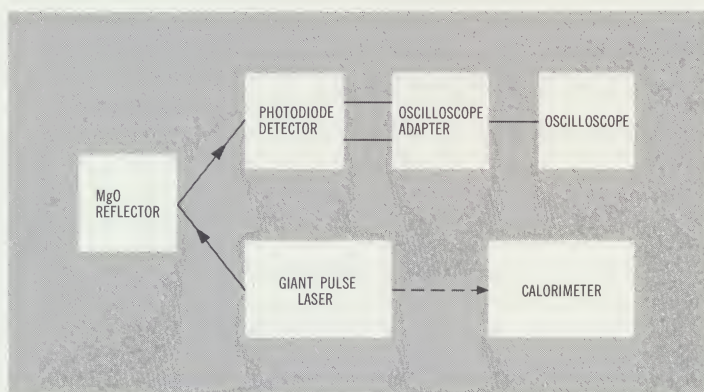
A new calibration must be made for each geometric configuration used. Rather accurate variations in the response sensitivity can be made, however, by using the inverse square law of the diffuse reflector. Care must be taken to avoid placing the diode so close to the reflecting block that the finite size of the beam affects the collection characteristics, or serious errors will be encountered.

BEAM DIVERGENCE

Beam divergence is, as previously noted, the rate at which laser radiation diverges as it radiates from the laser crystal. It is measured in milliradians.
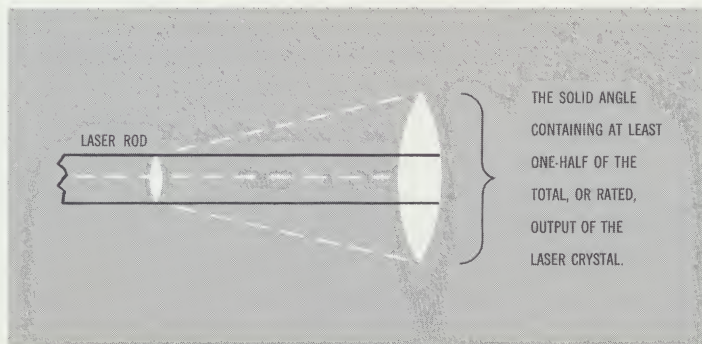
This spread of the beam as it leaves the rod is subject to considerable interpretation — particularly with respect to its exact definition and measurement.

Korad has run many experiments in an attempt to correlate data from both "cold" tests (those measurements on the laser rod made in a static or non-lasing condition) and "hot" tests (those made in conventional or giant pulse laser operation). To date, we have obtained very little quantitative agreement between hot and cold operation. The normal cold tests of Twyman-Green and gas laser beam diffraction frequently indicate that the beam divergence of the best ruby rods may have only 0.1 milliradian divergence per inch of length. Yet, these same rods in laser action may range anywhere from 0.25 to 0.75 milliradians divergence per inch of length.

The hot tests seem to provide the most accurate indication of beam divergence. Two methods have been used. The first is to measure the total output of the laser in either conventional or giant pulse operation. Suitable aperture stops are then placed in the focal plane of a long focal length lens until only one-half of the total energy remains. The size of the aperture and the focal length of the lens are utilized to determine beam divergence in milliradians. The only drawback of this technique is that at least 5 to 10 laser shots are required to accurately determine the exact half-power output level.

The second hot test method is more desirable in that it requires only one laser shot. This is particularly important with the very high power laser systems that have a finite life of optical components. In addition, this second method does not require an accurate pre-firing estimate of the expected energy output of the laser.

The first step in this method is to obtain the far field pattern of the laser output by either allowing the laser beam to expand of its own accord until the diameter of the projected spot is at least several times the diameter of the emitting source — or, by placing a long focal length lens in the beam with a diffusely reflecting white target at the focal plane of the lens. In both cases, angular divergence is translated into displacement.

The beam divergence can then be measured by photographing the far field pattern. Such a photograph will provide the beam divergence if the film is not saturated and if the density vs the exposure index (or gamma) of the film is precisely known. The gamma is difficult to predict. It is a function of the film type, the developing procedures, the particular batch from which the film was taken, and the wavelength. It is important, therefore, to use a photographic technique that does not require knowledge of the film gamma. To accomplish this, we have developed a special multiple lens camera. Each lens takes a separate exposure of the laser beam's far field pattern. A filter with an accurately known transmission at the wavelength of the laser is placed behind each of 16 lenses in the array. A step set of exposures is thus obtained covering two to three orders of magnitude (which provides a large tolerance to errors in obtaining the proper exposures).

The camera is focused on the diffuse reflector, the room

darkened, and the shutter opened. After firing the laser, the shutter is closed and the film developed. Although a positive print of the photograph is useful for a "quick look", the negative is used for the precise measurement of beam divergence. The exposure density across the centers of the beam patterns is plotted on a densitometer. The half-power point is determined. And, from the geometry of the photographic set-up, the beam divergence is obtained.

This procedure provides for accurate beam divergence measurement if the far field pattern of the laser is circularly symmetric. If such is not the case, the same basic technique can be applied but several tracings of the beam patterns must be made across a different portion of the exposure. From this, a contour plot of the beam pattern is constructed and a numerical integration is used to obtain the beam divergence. In this latter case, the exact definition of beam divergence depends upon the particular pattern that has been obtained from the laser beam.

Other Considerations

Test conditions are also important. For most experimental applications of the laser, measurements of peak power and beam divergence are so inter-related that a better method of specifying laser output may well be the **brightness** of the beam. (Brightness = watts per square centimeter per steradian. If the linewidth is included, this becomes **spectral brightness**.)

The inter-effect of beam divergence and peak power is shown in the following equations for two different systems. One has 3000 megawatts output with 10 milliradians beam divergence, using a ¾-inch ruby crystal. The other has only half the peak power output, but a 5-milliradian beam divergence.

$$\text{3.0 G.W. System Brightness} = \frac{3.0 \times 10^9}{\frac{\pi(\frac{3}{4} \times 2.54)^2}{4} \times \frac{\pi(10 \times 10^{-3})^2}{4}} = 1.34 \times 10^{13}$$

$$\text{1.5 G.W. System Brightness} = \frac{1.5 \times 10^9}{\frac{\pi(\frac{3}{4} \times 2.54)^2}{4} \times \frac{\pi(5 \times 10^{-3})^2}{4}} = 2.68 \times 10^{13}$$

As demonstrated in this example, a smaller beam divergence provides twice the **brightness** at one-half the peak power output. This same type of result occurs when Q-switched operation is obtained by use of passive Q-spoilers having spectral linewidths of the order of 0.02 Å — compared with Kerr-cell Q-spoilers with an ~0.6 Å linewidth. This would give a factor of 30 improvement in **spectral brightness.**
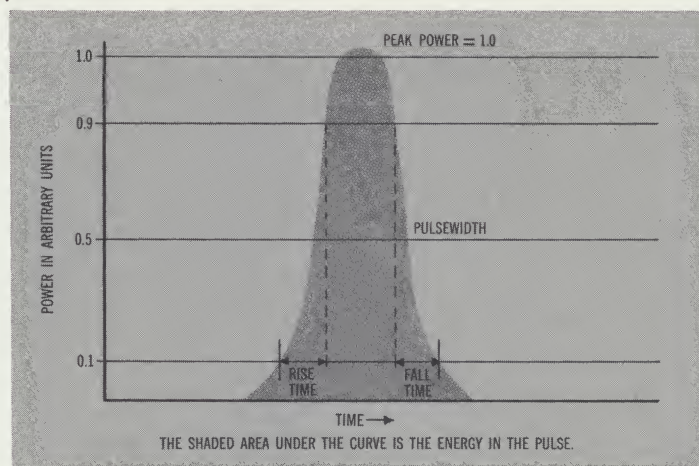
This criteria is important as high peak power laser systems approach the physical limits of today's materials. Extensive experiments have indicated that ruby crystal life is directly related to the output power level. For most practical purposes, the data reflected in the following plot of peak power vs probable number of shots illustrates the present operating limits for ruby. Similar data for other laser materials will undoubtedly be developed in the future.
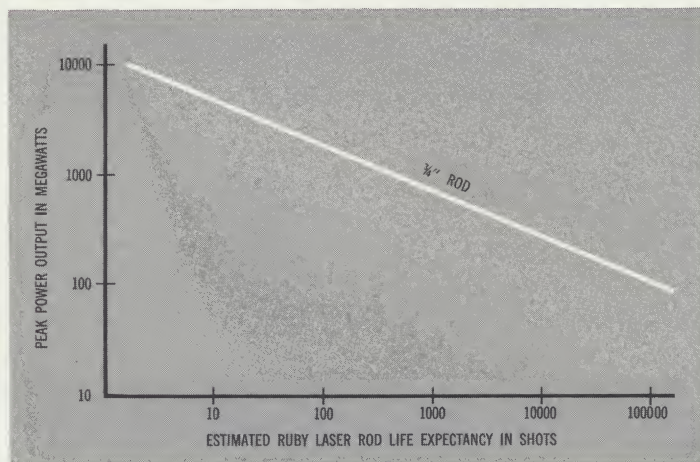
Another important consideration is output frequency. The output frequency for ruby at 20°C is red light, centered at 6943 Å. For minor excursions from 20°C, the variation is ~ 1 Å for each 20 C — ruby lasers operating in the conventional mode at liquid nitrogen temperature (77°K) have their output at 6934 Å.

SUMMARY
The following curve may also be of assistance to users. It demonstrates pictorially some of these important parameters.

THE SHADED AREA UNDER THE CURVE IS THE ENERGY IN THE PULSE.